Cartography, visual perception and cognitive psychology

Amy L. Griffin

Although they may be beautiful objects in their own right, maps require a map user to be made meaningful, even if in some cases the map user is the same person as the map maker. Early cartographers developed much of their understanding of which map design decisions worked and those that did not through trial and error rather than through systematic empirical study of how design decisions affected map use (Robinson, 1952). This is not to say that early cartographers did not seek any feedback on their work, but that this feedback was informal and ad hoc, rather than formal and systematic. One hallmark of twentieth-century cartography is its explicit acknowledgement of the importance of the map user (Montello, 2002).

The beginnings of ‘scientific cartography’

The nineteenth century was a period during which the organizational structures that we today call scientific disciplines began to emerge. As scientific knowledge grew, it became increasingly difficult for any one individual to master the existing state of knowledge (or even the most important knowledge) pertaining to a given topic (Weingart, 2010). This led to specialization and the differentiation of knowledge into different disciplines. As the splintering of science into different disciplines progressed, a new type of innovation emerged: the application of the theories and methods of one discipline to the object of study of another.

The first cartographer to suggest the value of a scientific approach to cartography was the German cartographer Max Eckert (see Chapter 1, this volume), who declared in 1908 that ‘I should, therefore like to designate one of the most important topics that scientific cartography has to deal with: “map logic”. Map logic treats of the laws which underlie the creation of maps and which govern cartographic perception’ (Eckert, 1908: 348). He expanded upon these ideas in a 1500-page, two-volume exposition that argued for the application of psychological theories and research to establish the laws of map logic (Eckert, 1921, 1925). From citations of Wilhelm Wundt’s work that appear in Die Kartenwissenschaft, it is clear that Eckert was both aware of and influenced by Wundt’s establishment of the discipline of experimental psychology in Germany 1879 (p.636).

As a discipline concerned with the study of human behaviour and mental processes, psychology investigates topics such as perception and cognition, among others. Perception concerns
how the brain brings meaning to sensation by organizing, identifying and interpreting sensory information. Biologically, perception is important because it provides us with information that is critical to how we interact with our environment. Cognition is also concerned with meaning making. However, its study moves beyond understanding the role of sensation in constructing meaning to also include mental processes such as attention (focus), memory, and use of existing knowledge and/or experience.

Like many other design disciplines in the twentieth century, cartographers embraced the modernist principle that ‘form should follow function’, implying that functional design was the highest design goal. One of cartography’s strongest advocates for the idea that form should follow function was Arthur Robinson, who reiterated Eckert’s entreaty for a science of cartographic design, one based on the limits of human perception, in his 1952 book, The Look of Maps. This opened the door to research using psychological methods for defining those limits as they applied to using maps.

Implicit in the concept of functional design is that the designer can foretell and specify the designed object’s intended function. Otherwise, there is no standard against which to measure the design’s ‘quality’, that is, its efficacy and/or efficiency (Olson, 2015). In some cases, the intended ‘function’ of a map is to simply communicate the spatial distribution of a particular phenomenon. Indeed, in Robinson’s (1952) view, scientific cartography existed to transmit scientific information from a scientist to the map user (p.17).

The process by which this information transmission occurred eventually became known as the theory of cartographic communication, a topic of intense interest in the 1960s and 1970s. A key point of focus in this research was the relationship between how the cartographer’s design decisions influenced the graphical marks on the page and what information those marks allowed a map user to perceive and extract from the map. The topic of cartographic communication was considered of sufficient importance to warrant the establishment of Commission V of the International Cartographic Association in 1972. The goals of this commission included defining the principles of map language (similar to Eckert’s ‘map logic’), evaluating the effectiveness and efficiency of communication between the map maker and the map user afforded by this language, and establishing theory that described how information was transmitted between the two parties (Ratajksi, 1974). Central to the goals of this commission were map perception experiments that sought to establish the relationship between the marks on the page and what the map user perceived.

**Visual perception: seeing map symbols**

A number of authors distinguished between signal (i.e. the message being communicated) and noise (i.e. graphical marks that distract the map user from understanding the message the cartographer intends to transmit). Noise might be generated by the inclusion of unnecessary map information or failing to use the correct principles of map logic to represent map information. The concept of visual hierarchy (see Figure 3.1) and the perceptual principles, such as Gestalt theory that enable its construction within a map by a cartographer, are examples of how using appropriate (for the communication goal) map logic can improve the likelihood that a map user will receive the intended map message (Wood, 1968). Visual hierarchy refers to the apparent separation of map symbols into different depth planes within the map. Gestalt theory is a psychological theory that proposes a series of graphical characteristics that lead to the perception of grouped elements; cartographically, the grouping of map symbols into different planes of visual hierarchy.

Wood did not do any empirical testing himself, but he drew extensively on his reading of the visual perception literature from psychology. Much later, cartographers did assess the effects
of matching map and information logics through visual hierarchy in maps used in power plant control rooms and air traffic control towers. The findings of these studies confirmed Wood’s contention that appropriate visual hierarchy improves map user performance – leading to more efficient use of displays, lower perceived mental effort required to use the maps, and similar error rates to displays designed without visual hierarchy (Van Laar and Deshe, 2002, 2007).

Work within psychology has further helped cartographers to develop rules of thumb for creating visual hierarchy by identifying which visual variables are pre-attentively processed by the eye-brain system (Treisman and Gelade, 1980; Treisman, 1985; Fabrikant and Goldsberry, 2005; Fabrikant et al., 2010). Pre-attentive processing leads to particular features of the display appearing to ‘pop out’, as was seen in Figure 3.1, without the map user needing to inspect each individual symbol in turn. While it is very easy to quickly identify all the red symbols in the map below because colour hue is pre-attentively processed (Figure 3.2), it is difficult to identify all square symbols at a glance, because shape is not pre-attentively processed. Things become more complicated when visual variables are combined. For example, it takes a long time to differentiate between blue squares and blue circles because the combination of colour hue and shape is not pre-attentively processed, and it therefore requires serial visual search in the display.

Noise could also result from incorrect messages being received by the map user as a result of human perceptual (in)abilities, such as those uncovered in psychophysical map design experiments. Psychophysical map design experiments attempt to identify the relationship between variations in some aspect of the graphical marks on the page and how map users perceive these differences. Cartographic experiment designers working in this tradition typically saw the problem of map design as a technical one that could be solved by optimizing the design to account for human perceptual capabilities – improving the efficiency and effectiveness of

---

Figure 3.1  Left: While the Gestalt principle of good continuation makes it possible to differentiate rivers from contour lines, the visual hierarchy is weak. Right: The Gestalt principle of similarity (of colour) is added to more clearly separate the two types of line symbols onto separate visual planes, improving the map user’s understanding of which line symbols belong to which real-world phenomenon.
map communication (Liben and Downs, 2015). For example, one large group of experiments, the first of which was conducted by Flannery, focused on the relationship between the area of a proportional-area symbol (often circles) and the area the map user perceived that the symbol covered (Flannery, 1956). While later research showed that these relationships were both context- and user-dependent, several cartography textbooks recommended that cartographers adjust the scaling of proportional symbols to account for map users’ tendency to underestimate the area of symbols. This adjustment, whether equally effective for all individuals and contexts or not, has made its way into prominent map design software tools.

Psychophysical research on maps also provided an early focus on human discrimination of visual symbols on maps (Griffin and Montello, 2015). In these symbol discrimination experiments, the goal was to produce information that would allow cartographers to construct a set of visually discriminable map symbols, within the context of the map production
technologies in use at the time. Work in this area focused on several types of symbols: gray-scale tones (e.g. Williams, 1958), colour hues (e.g. Brewer, 1997), shape (e.g. Forrest and Castner, 1985) and typeface characteristics (e.g. Shortridge and Welch, 1982). A key commonality in the findings of these studies was that map context was a critical element in determining whether two symbols would be discriminable: increasing difficulty in discrimination the ‘noisier’ the map context (Figure 3.3).

This difficulty in predicting the exact effect of a map design decision for a particular map and for a particular map user led some cartographers to become disenchanted with perceptual map design research (Petchenik, 1983). At the time, although computers were becoming more commonly used to design maps, the thought of personalized maps that are customized for one person and one map use context was unimaginable; today, it is a distinct possibility (e.g. Huang et al., 2014; Reichenbacher, 2005). Nevertheless, computers, because of the flexibility they enabled for designing maps, did allow for more rapid progress to be made in testing the effectiveness of cartographic design conventions (Experimental Cartography Unit, 1971). Another impact of the computerization of map production was the introduction of map design ‘defaults’ that are built into software. Although individual differences between map users mean that a map that works well for one person may not work well for another person, implementing map design defaults based on the results of map perception studies can still lead to improvements for many map users. A practical example of this is the implementation of ColorBrewer colour schemes (Harrower and Brewer, 2003; Brewer, 2003) in many map design software packages.²

![Figure 3.3](image)

**Figure 3.3** The problem of simultaneous contrast makes it difficult to discriminate between two colour hues, especially when there are many competing hues nearby. The two marked polygons are in fact the same colour.
Visual cognition: making sense of map symbols

While research on visual perception can help us to understand some of the constraints within which cartographers work when designing a map, much of the early work in this area did not sufficiently acknowledge the role of cognitive processes such as attention and memory in map use. For example, what a person sees is affected not only by the character of the graphic marks on the page but also by her experience and knowledge of reading maps and the subject of the map, and her expectations of what she will see, which may influence where she looks (MacEachren, 1995).

From the 1920s until the publication of Ulric Neisser’s *Cognitive Psychology* in 1967, behaviourism was a dominant paradigm within psychology. Behaviourism sought to understand behaviour by measuring observable behaviours and was assumed to be determined by conditioning; interactions with the ‘environment’. Neisser’s (1967) innovation was to suggest that mental processes were important for understanding behaviour and that people’s mental representations were constructed, often on the fly and to suit a particular context or task. While Neisser’s book was not the first writing to propose some aspects of what has become known as the cognitive paradigm, it was a cogent presentation of an alternative to behaviourism.

A significant new approach for understanding cognitive processes was the use of eye tracking to identify where visual attention was or was not focused on the map. Early eye trackers were used in fields other than cartography, to study behaviours such as reading, or viewing art or photographs (e.g. Buswell, 1935; Yarbus, 1967; Huey, 1968 [1908]). In the early 1970s, psychologists began to suggest that eye movements could be used as evidence of mental processes (Noton and Stark, 1971). This idea eventually became known as the strong eye-mind hypothesis (Just and Carpenter, 1980). Others challenged this idea by demonstrating covert attention, where a person can pay attention to something at which they are not looking (Posner, 1980). Today, researchers acknowledge that eye movements probably slightly lag behind attention, meaning that fixations (where the eye is focused for a relatively long period) provide at least some indication that the person’s attention was focused on that location (Hoffman, 1998).

Eye tracking was introduced to cartographers by psychologist Leon Williams at the Symposium on the Influence of the Map User on Map Design in Canada in 1970 (Steinke, 1987). Thereafter followed a number of early experiments, in which map users’ eye movements were recorded in a free viewing task – that is, participants were told to just read the map (Jenks, 1973; Dobson, 1979). These researchers were surprised to find a wide variety of viewing patterns between individuals, though most map users did seem to spend more time looking at informative parts of the map compared with less informative parts of the map.

Others identified the importance of using a map use task to prompt the map user to activate specific cognitive processes and thereby be able to come to firmer conclusions about the relationship between map design and the cognitive processes map users employed (Steinke, 1987). DeLucia (1976: 143) reiterated the importance for map use studies of link between form and function by concluding:

> the most useful and meaningful standard against which all maps should be designed and subsequently evaluated is FUNCTION. From the beginning we must design our maps to enable some human user to perform some functional act or operation … As we have seen over and over again in the experimental records of this research, the nature of the task or function to be performed by the map user is the single most important factor in determining how [author’s emphasis] he processes the information on the map.
Here, it is possible to see the beginnings of the idea that maps that are designed to support a given task will be more effective if they lessen the cognitive load of the map user – that is, they direct the map user’s attention to the most informative parts of the map with minimum effort.

Early eye tracking experiments were technically difficult to carry out given the equipment available at the time (some were recording reflections on the surface of the eye on film), and the data they produced were very time consuming to analyse. This, in addition to the fact that they did not truly allow cartographers to see what was going on in the map user’s head, led to a lull in the use of eye tracking in the 1990s. But development of cheaper, digital video-based eye trackers that measure the corneal reflection of infrared light on the eye, in combination with computer programs that can be used to preprocess eye movement data and reduce the time spent analysing data, has led to the reemergence of the technique in cartographic research. Today’s eye tracking applications often combine the method with other ways of measuring cognitive processes, such as verbal protocols (e.g. Peebles et al., 2007) or usability metrics (Çöltekin et al., 2009; Manson et al., 2012) and experiments include both those conducted in controlled laboratory settings and on mobile devices used for navigation and delivering location-based services (e.g. Kiefer et al., 2014).

Cartographic researchers using eye tracking have found that there are influences of both the design of the map and the map task on visual attentive behaviour (e.g. Fabrikant et al., 2010). This provides evidence that visual information processing depends both on visual perception, through what is known as bottom-up encoding mechanisms that occur in early, pre-attentive vision, and cognitive processes and strategies, through what is known as top-down encoding mechanisms that interact with a map user’s existing knowledge. Neisser (1976) introduced this idea as the ‘perceptual cycle’.

Cognitive processes and strategies include things like knowing where to look within a display, and interpreting information found within a map based on other knowledge stored in long-term memory. Therefore, we might expect different map users to have and use different information stored in memory when interpreting maps. For example, geologists may have detailed knowledge about characteristic 3D structures of geological formations that they draw upon when using a geological map, whereas map users without geological training may not have this knowledge. Schemata are mental structures that the map user employs to mediate between what s/he already knows and what s/he sees in a map. In other words, they are the means by which the map user constructs information from visual representations like maps. They are used to both organize information and plan behaviour and can be modified by new information.

MacEachren (1995) contends that map use probably involves using both general map schemata and specific map schemata. A general map schema might include things like understanding that legends provide explanations of the real-world phenomena for which map symbols stand, while a specific map schema could involve filling in the details of the general schema, such as understanding that blue means cool temperatures while red means warm temperatures. An individual map user may or may not have developed a particular specific map schema through training or past experience with that type of map. Following on with the geological map user example, many geological maps use a standard set of symbols for identifying specific features of geological interest, and an experienced geologist would possess the schema for interpreting these symbols, while the average layperson would likely not and would need to spend more time consulting and referring to the legend while using the map. Some cartographers have provided evidence in support of the idea that the use of specific legend designs can prompt the use of helpful map schemata and enable more effective use of the map for the task at hand (see Figure 3.4).
One such example is DeLucia and Hiller (1982), who found that showing hypsometric tint symbols using a legend that modelled a hill (a ‘natural’ legend design) helped map users to complete map use tasks that required visualizing the shape of the terrain.

Understanding the map schemata that map users activate can help cartographers design maps that can be used with less cognitive effort, that is to say, cognitive load. Bertin (1983 [1967]) characterized such maps as ‘maps to be seen’ rather than ‘maps to be read’. Maps to be read require effortful extraction of information from the map. The various map design guidelines such as Bertin’s visual variables, and later extensions and modifications thereto can be seen as one kind of attempt to formalize specific map schemata (MacEachren, 1995). Nevertheless, many map design guidelines have not been empirically evaluated to test how well they function as map schemata (some exceptions include Garlandini and Fabrikant 2009; MacEachren et al., 2012).

But not all maps have communication as their primary function. MacEachren and Monmonier (1992) coined the term geographic visualization to describe the practice of using maps for thinking and reasoning about geographic problems, most particularly when the maps could be produced at the speed of thinking via interacting with a computer. In an attempt to move cartographic research beyond its (then) recent focus on maps used for communication, MacEachren and Ganter (1990) proposed a model of how thinking with maps might work. It too referenced Neisser’s perceptual cycle, but also suggested that the ‘seeing’ produced by the combination of bottom-up and top-down encoding then interacts with knowledge schemata (both general and domain-specific ones) to produce inference and reasoning. Their model proposed iterative refinement of both the maps produced by interaction with the computer and the hypotheses produced by inference and reasoning. They further argued that to support truly original thinking and insight, it might be necessary to break existing schemata to shift the thinker’s perspective on the problem. While schemata can be supportive of reasoning by enabling the map user to match their schemata to a visual display in order to interpret what s/he sees, they

Figure 3.4 A legend whose symbols vary in size in proportion with their prevalence on the map might prompt the use of schemata related to statistical distributions. Dykes et al. (2010) provide an alternative design concept for this in their ‘Legend as Statistical Graphic’ theme
can also cause the map user to miss something that is unexpected because it does not fit neatly with their currently used schemata.

Conclusions

The scientific cartography project begun by Eckert and Robinson has borne many fruit. Consideration of the map user is now firmly entrenched in the practice of contemporary cartography, at least as practised by professional cartographers. Old rules of thumb and cartographic conventions have been studied and the application of psychological theories about perception and cognition have helped us to understand whether and why their design (form) enables a particular type of functional map use. Some of this research, particularly those results that can be successfully applied to maps used for communication, has made its way into everyday practice, with ColorBrewer perhaps the standout success. Much more work remains to be done, especially in understanding how maps help people to make inferences and decisions. Continued engagement with psychology, cognitive science, and neuroscience research will be critical for supporting future progress.

Notes

1 Robinson (1952: 18) even went so far as to suggest that beauty might be undesirable in a map as it might distract from the map user’s intellectual response to the map.
2 The influence of ColorBrewer extends well beyond map design software. Its colour schemes are implemented in several information graphics design and statistical analysis software packages.
3 MacEachren and Ganter (1990) originally called this idea cartographic visualization, but MacEachren later came to prefer the term geographic visualization (MacEachren, 1994), and it has since been shortened in common usage to geovisualization.
4 The rise of the amateur mapmaker presents many challenges for cartographers – chief among them the question of how they can help amateur mapmakers create more usable maps.

References


53